

The Broadband Spectral Energy Distribution of the MOJAVE Sample

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Abstract. We are constructing the broadband SED catalog of the MOJAVE sample from the radio to the γ -ray band using MOJAVE, *Swift* UVOT/XRT/BAT, and *Fermi*/LAT data, in order to understand the emission mechanism of extragalactic outflows and to investigate the site of high-energy emission in AGN. Since the launch of *Fermi* γ -ray Space Telescope in August 2008, two thirds of the MOJAVE sources have been detected by *Fermi*/LAT. Combining the results of high-resolution VLBI, X-ray, and γ -ray observations of the jet-dominated AGN sample, we want to pin down the origin of high-energy emission in relativistic jets. Here we present our overall project and preliminary results for 6 selected sources.

1. Introduction

Blazars are extremely powerful objects which only represent a small subset of active galactic nuclei (AGN), yet they dominate the extragalactic radio and high-energy sky. Blazars are those AGN whose jet is pointing towards us, which results in strong Doppler-boosting of the emitted radiation. The small viewing angle is also responsible for the superluminal jet motions observed in their jets. Since August 2008, the *Fermi* Large Area Telescope (LAT) is performing a continuous all-sky survey in γ -rays. After one year of operation, *Fermi*/LAT has detected 709 AGNs, of which 85% are blazars (Abdo et al. 2010b). The Monitoring Of Jets in Active galactic nuclei with VLBA Experiments (MOJAVE) program has monitored a radio-selected sample of 135 AGNs since the mid-1990s (J2000.0 declination $\leq -20^\circ$; galactic latitude $|b| \leq 2.5^\circ$; 15 GHz VLBA flux density ≤ 1.5 Jy), and most of the MOJAVE sources are blazars due to the selection criteria (see details in Lister et al. 2009a; Lister 2010). In the one-year AGN catalog of *Fermi*, two-thirds of the MOJAVE sources are detected (Boeck 2010). Based on theoretical models, it is suggested that the γ -ray and radio emission in blazars are closely connected (Dermer & Schlickeiser 1993; Sikora et al. 1994). Dermer & Schlickeiser (1994) proposed that the γ -ray emission from highly-beamed relativistic AGN outflows originates near the base of the jet. The high-resolution capability of very-long-baseline interferometry (VLBI) enables us to pin down the structure of extragalactic outflows up to the scale of sub-parsecs, and to trace component ejections and evolution along jets.

To understand the physical mechanisms ongoing in blazar jets, one of the best approaches is to study the broadband spectral energy distribution (SED). By using the multi-frequency data and investigating the correlations, one can apply theoretical models to the broadband emission to constrain further the parameters in the local frame of AGN jets.

2. The SED catalog of MOJAVE sources

We want to investigate the broadband SED properties of the complete radio-selected MOJAVE sample. All of the MOJAVE sources are X-ray emitters (Kadler 2005), and recent results also show that the γ -ray brightness of AGN is correlated with VLBI jet properties (Kovalev et al. 2009; Pushkarev et al. 2009; Savolainen et al. 2010; Lister et al. 2009c; Ojha et al. 2010). A *Swift* fill-in survey has been conducted since 2007 for the MOJAVE sample (P.I.: M. Kadler), providing optical, UV, and X-ray observations. As bright, well-studied radio sources, the MOJAVE sources have very good flux-density sampling in the radio band. Combining the *Fermi*/LAT results, we are constructing the broadband SED catalog from the radio to the γ -ray band of the 135 MOJAVE sources of the statistical complete sample. Our goal is to study their characteristics, and to determine the correlations of the emission properties between different bands. In the MOJAVE sample, there are 101 flat-spectrum radio quasars, 22 BL Lac objects, 8 radio galaxies, and 4 unidentified AGNs. In the following sections, the broadband SED data acquisition will be introduced. We will show preliminary results of 6 selected

Table 1. Multi-wavelength facilities from the radio to the γ -ray bands that are used to construct the MOJAVE SED catalog.

Facility	Band	Frequency (Hz)
VLBA ^a	Radio	1.5×10^{10}
UMRAO	Radio	$(4.8, 8, 14.5) \times 10^9$
Effelsberg ^b	Radio	$(2.6, 4.9, 8.4, 10.5, 14.6, 23, 32) \times 10^9$
IRAM ^b	Millimeter	$(8.6, 14.2, 22.8) \times 10^{10}$
<i>Swift</i> /UVOT	UV-Optical	$(5.5, 6.9, 8.6, 11.3, 13.4, 14.8) \times 10^{14}$
<i>Swift</i> /XRT	X-ray	$(7.25-242) \times 10^{16}$
<i>Swift</i> /BAT	X-ray	$(3.6-36) \times 10^{18}$
<i>Fermi</i> /LAT	γ -ray	4.8×10^{21} to $> 7.3 \times 10^{24}$

^a MOJAVE program.

^b F-GAMMA project.

sources which have good broadband SED data coverage. All sources are in the *Fermi* first-year catalog, and were not included in the SED study of *Fermi* LBAS sample (Abdo et al. 2010a). We will discuss the preliminary results.

3. Data acquisition and analysis

Here we introduce the instruments and characteristics of the data included in the MOJAVE SED catalog. In the γ -ray band, we included the result of the 11-month *Fermi*/LAT catalog (Abdo et al. 2010b). We used the X-ray telescope (XRT) and burst alert telescope (BAT) onboard *Swift* to cover the X-ray band, and we used the *Swift* UV-optical telescope (UVOT) for UV and optical band data. For each of the MOJAVE sources, we reduced one epoch of *Swift* XRT/UVOT data observed after August 2008 with the longest XRT integration time. Many of the MOJAVE sources are weak in X-rays, and typically we used epochs with XRT integration time around 5–10 ksec. For the sources with no recent data, we submitted *Swift* Target-of-Opportunity (ToO) observing requests. As of May 2010, only 5% of the MOJAVE sources have no *Swift* data after August 2008, and are waiting observation. Table 2 summarizes our results of *Swift*/XRT data analysis, together with other relevant parameters of the 6 sources.

The 26-meter radio telescope in the University of Michigan Radio Astronomy Observatory (UMRAO) has monitored a large number of AGN for the past four decades (Aller et al. 1985, 2003), including all MOJAVE sources. Here we included the UMRAO data closest in time to the *Swift* observation used. We also included the Effelsberg 100 m telescope and the IRAM 30 m telescope observations in the framework of the *Fermi*-GST AGN Multi-frequency Monitoring Alliance¹ (F-GAMMA; Fuhrmann 2010; Angelakis 2010). Also, we included the broadband historical data from the NASA/IPAC

Extragalactic Database² (NED). Table 1 lists the facilities and wavebands covered in our study.

4. Results

We selected 6 of the MOJAVE sources with good data coverage, and present the preliminary SED here (see Fig. 1). The presented sources are three flat-spectrum-radio quasars, two BL Lac objects, and one radio galaxy (see Table 2). All of them are in the *Fermi* first-year catalog, but were not included in the broadband SED study of *Fermi* LBAS sample (Abdo et al. 2010a).

The SEDs of the 6 MOJAVE sources show a classical double-peak blazar shape (Dermer & Schlickeiser 1993). Current models suggest that the major part of emission from blazars are non-thermal, and the low-energy peak (10^7 – 10^{16} Hz in Fig. 1) is due to synchrotron emission from the radio jet, and the high-energy peak (10^{17} – 10^{27} Hz in Fig. 1) can be interpreted as inverse Compton emission of various radiation sources, e.g., synchrotron self-Compton (SSC; Jones et al. 1974; Ghisellini & Maraschi 1989) and external radiation Compton (Sikora et al. 1994; Dermer & Schlickeiser 2002). The physical processes involved in the SED study are complex, and the fact that we cannot distinguish different emission regions from a target source makes broadband SED modeling challenging. For example, the SED study of 48 *Fermi* bright blazars (Abdo et al. 2010a) shows that a homogeneous one-zone model with SSC mechanism cannot explain most of their results, and more complex models involving external Compton radiation or multiple SSC components are needed to model the blazar SEDs. In Fig. 1, we present the SED of the 6 sources in ν - ν F $_{\nu}$ plots. We performed a mathematical polynomial fit of 2nd to 4th order to the two humps, providing numerical values of the peak positions of the synchrotron and inverse-Compton components. Also, the total energy output of the low- and high- energy humps could be estimated from the polynomial fit. From Fig. 1, one can see that in each source, the total energy output of the low- and high- energy components differs. The high-energy hump of B0754+100 is significantly lower than the low-energy one, whereas the other sources have comparable height of the two humps. We discuss the 6 individual sources below.

B0300+470 4C +47.08 is a BL Lac object, which shows a compact asymmetric morphology in VLBI observations (Lister et al. 2009a). It displays a one-sided halo at kiloparsec scale. This source is variable on a monthly timescale at centimeter wavelengths (Aller et al. 1985) in total flux and linear polarization, and the source is core-dominated (Nan et al. 1999). We analyzed one epoch of *Swift* observations of this source obtained in September 2008 (ID 00036235005) with an integration time of 7 ks.

¹ The full F-GAMMA team, see

<http://www.mpifr-bonn.mpg.de/div/vlbi/fgamma/teams.html>

² <http://nedwww.ipac.caltech.edu/>

Table 2. Summary of our X-ray and the γ -ray measurements of Abdo et al. (2010b) of the 6 sources in this study.

IAU Name	1LAC 1FGL	Source type	z	β_{app}	F_X [10^{-13} erg cm $^{-2}$ s $^{-1}$]	F_γ [10^{-13} photon MeV $^{-1}$ cm $^{-2}$ s $^{-1}$]	α_X	α_γ
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
B0300+470*	J0303.1+4711	B	-	-	7.38	49.9 ± 7.9	1.38 ± 0.41	2.56 ± 0.13
B0415+379	J0419.0+3811	G	0.049	5.9 ± 0.1	454	76.3 ± 15.8	1.73 ± 0.01	2.61 ± 0.16
B0754+100	J0757.2+0956	B	0.266	14.4 ± 1.2	29.8	75.2 ± 6.7	1.81 ± 0.08	2.39 ± 0.08
B0836+710	J0842.2+7054	Q	2.218	25.4 ± 1.0	122	366 ± 32	1.43 ± 0.02	2.98 ± 0.12
B1730–130	J1733.0–1308	Q	0.902	35.7 ± 2.1	12.1	85.4 ± 7.6	1.98 ± 0.33	2.34 ± 0.07
B2209+236	J2212.1+2358	Q	1.125	3.4 ± 0.5	4.80	3.3 ± 0.7	1.43 ± 0.60	2.13 ± 0.19

(1) Source Name; (2) The first LAT AGN catalog name (Abdo et al. 2010b); (3) Optical class (B: BL Lac, G: radio galaxy, Q: quasar); (4) Redshift; (5) The maximum apparent projected speed measured by the MOJAVE team (Lister et al. 2009b); (6) X-ray flux measured by *Swift*/XRT (0.2–10 keV); (7) γ -ray flux measured by *Fermi*/LAT using 11-month data (Abdo et al. 2010b); (8) X-ray photon index; (9) γ -ray photon index.

* Luminosity distance unknown, measured maximum apparent speed 287 ± 23 μ as yr $^{-1}$.

B0415+379 3C 111 is a well-studied broad-line radio galaxy which shows a classical Fanaroff and Riley Class II morphology on kiloparsec scales (Linfield & Perley 1984). It hosts a highly collimated one-sided jet emitting from the central core to the northeastern lobe (see e.g., Kadler et al. 2008). 3C 111 is associated with the EGRET source 3EG J0416+3650, and the broadband SED study of the historical data suggests that the SED profile is similar to EGRET flat spectrum radio quasars (Hartman et al. 2008). Here we analyzed *Swift* data observed in January 2010 (obsid 00036367005) with an integration time of 9 ks.

B0754+100 B0754+100 is cataloged as a low-frequency peaked BL Lac (LBL) by Fiorucci et al. (2004). By the blazar classification of Abdo et al. (2010a), B0754+100 is a low synchrotron peaked blazar ($\nu_{\text{peak}} \leq 10^{14}$ Hz) based on our fitting result. VLA observations showed that there is a diffuse halo around the core at 1.5 and 5 GHz up to scales of >120 kpc (Antonucci & Ulvestad 1985; Kollgaard et al. 1992). Recently, B0754+100 was reported to be flaring in the near-infrared band (Carrasco et al. 2010). We requested *Swift* ToO request for this source, which was observed in February 2010 (obsid 00036195002) with an integration time of 9 ks.

B0836+710 4C +71.07 is a luminous quasar which hosts a radio jet extending up to kiloparsec scales. Broadband variability was observed in this source (Otterbein et al. 1998), and space VLBI observations have revealed detailed jet structures (Lobanov et al. 1998; Perucho & Lobanov 2007). Here we included the *Swift* data of B0836+710 observed in February 2009 with an integration time of 9 ks (obsid 00036376005).

B1730–130 NRAO 530 is a high-polarized radio quasar which hosts a double-sided kilo-parsec scale jet. This source is actively variable in the radio (Marscher & Broderick 1981; Feng et al. 2006), optical (Pollock et al. 1979), X-ray (Foschini et al. 2006),

and γ -ray (Hartman et al. 1999) wavebands. We used the *Swift* data of NRAO 530 observed in June 2009 with an integration time of 5 ks (obsid 00035387012).

B2209+236 B2209+236 is a core-dominated flat-spectrum radio quasar. The radio turn-over frequency of this source is above 5 GHz (Dallacasa et al. 2000), which indicates that the source is very compact and is possibly young. Here we used the *Swift* observation obtained in April 2009 with an integration time of 9 ks in the SED study (obsid 00036359002).

5. Outlook

As of May 2010, we completed the data collection and construction of quasi-simultaneous SEDs during the time between August 2008 to July 2009. Almost all sources have nearly simultaneous observations from radio to X-ray with good data coverage. We are compiling the statistical properties of the 135 sources (e.g., correlation study between VLBI properties, X-ray and γ -ray parameters, and broadband SED characteristics), and the results will be presented elsewhere (Chang et al., in preparation). Physical SED models will be applied to the whole sample, to shed light on the mechanisms of general AGN picture.

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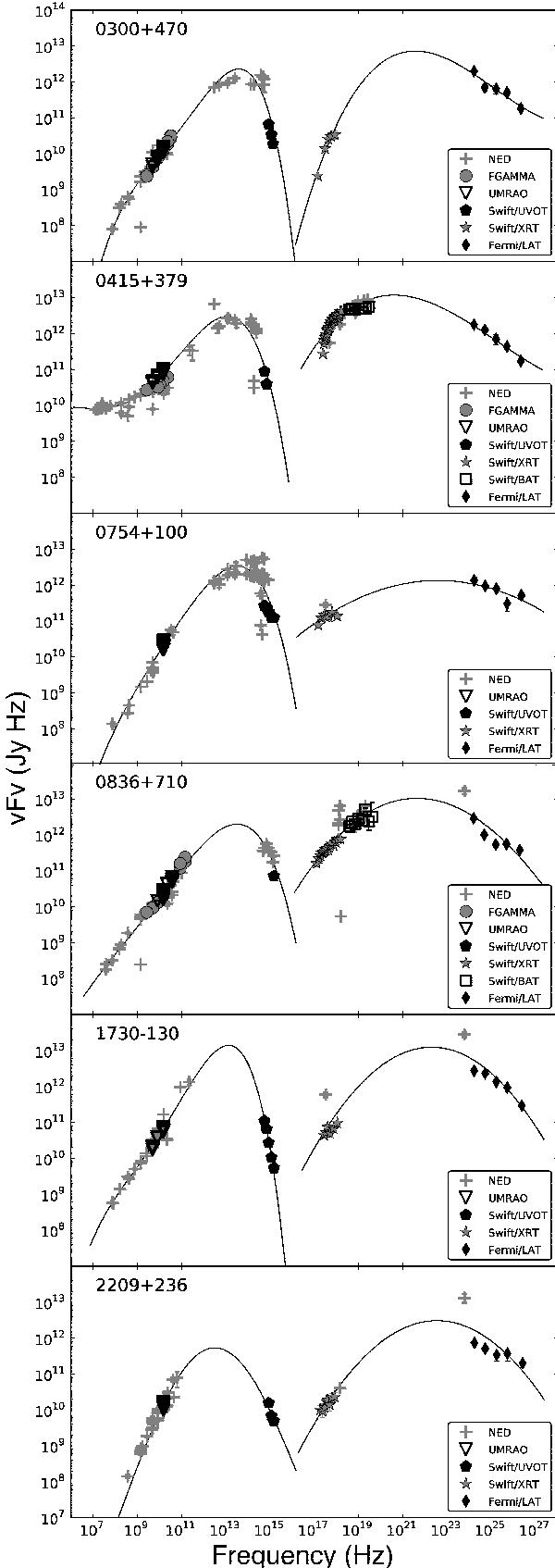


Fig. 1. The broadband spectral energy distribution of 6 selected MOJAVE sources. Polynomial fitting results are shown as solid lines.

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